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The protective role of canopy cover against cork oak decline in the face of climate change

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Abstract

Cork oak (*Quercus suber* L.) mortality has reached alarming proportions in the last decades, exacerbated by climate change. Understanding this phenomenon is crucial in finding mitigation or adaptation strategies. This study conducts a diachronic analysis of cork oak mortality over 10 years using GIS (Geographic Information Systems) tools, focusing on Portugal's Tagus Lezíria region. Topographic, edaphic and climatic variables were employed to create maps of edaphoclimatic aptitude for cork oaks. Dead trees were identified using remote sensing techniques and crown coverage was determined to calculate the trees' mortality index. The diachronic analysis aimed the exploration of climate change effects on cork oak mortality. A decrease in precipitation was observed, significantly impacting stands with canopy cover below 40%. Furthermore, a negative effect of solar radiation identified only in stands with canopy cover of 40% suggested its role in cork oak decline. This study introduces a novel perspective, highlighting the protective effect of denser canopy cover against excessive solar radiation and the impact of reduced precipitation. The integrated and diachronic approach provides valuable information for adapting management strategies to climate change challenges.

Key words: tree mortality; forest management; solar radiation; diachronic study; climatic resilience

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1. Introduction

The cork oak (*Quercus suber* L.) not only makes up for a significant part of the Western Mediterranean forest but it also retains great socio-economic relevance, especially in the Iberian Peninsula. The decline of such perennial oaks as well as the exploration systems they are part of – *montados* and forest stands – has been taking alarming proportions (Natividade 1950; Macara 1975; Brasier et al. 1993; Scarascia-Mugnozza et al. 2000; Sousa et al. 2007; Camilo-Alves et al. 2013; Pinto-Correia & Godinho 2013), which is why several lines of research have been explored in order to understand this degradation process as well as to find possible solutions to mitigate and/or reverse it. Numerous studies are already published regarding cork decline. In the 1980/90's, after significant mortality outbreaks in Portugal and Spain, affecting both cork oaks and holm oaks (*Quercus rotundifolia* Lam.), the presence of the radicular pathogenic agent *Phytophthora cinnamomi* Rands was detected within the areas most affected by mortality events (Brasier et al. 1993). Subsequent works showed the importance of several other biotic and abiotic factors related to tree mortality events, for example, prolonged drought events, soil limitations to root development and improper management practices (Brasier et al. 1993; Cabral et al. 1993; Lloret & Siscart 1995; Ferreira et al. 2001; Peñuelas et al. 2001; Ferreira et al. 2007; Ribeiro & Surový 2008; Camilo-Alves et al. 2013; Ribeiro et al. 2016; Camilo-Alves et al. 2020). Camilo-Alves et al. (2013) conceptualized the tree mortality process as a decline spiral, where the combination of several factors acting in synergism causes trees to decline, which can be grouped into (1) predisposing factors – usually permanent factors such

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as site characteristics; (2) inciting factors – that are transient, such as pests and diseases, incorrect forestry management or drought events; (3) contributing factors – opportunistic diseases such as charcoal disease caused by *Biscogniauxia mediterranea* Kuntze (Santos 2003). In addition to biotic and edaphoclimatic factors, cultural practices in forestry management are associated with tree decline, including examples such as high bovine density and soil mobilization for pasture sowing and/or shrub control, compromising natural regeneration and tree vitality, as already studied and demonstrated (Cabral et al. 1992; Camilo-Alves 2014; Dinis 2014; Raposo & Gomes 2014; Dinis et al. 2015; Godinho et al. 2016; Listopad et al. 2018; Camilo-Alves et al. 2020; Raposo et al. 2020). Furthermore, tree mortality events may be aggravated by the climatic changes expected for the Mediterranean, such as droughts with greater frequency, durability and intensity, even more considering they might be followed with possible absence of wet winters (Giorgi & Lionello 2008; Böhnisch et al. 2021). This trend has been verified by the latest IPCC report indicating a warmer and drier Mediterranean region during the last few years (Calvin et al. 2023).

Cork oak trees are mainly explored in agro-silvopastoral stands (ICNF 2019a), named *montados* which are multifunctional systems of anthropic origin, with oaks in open and irregular stands and an understory composed by shrubs, agriculture or pasture, sharing the same development space, resulting in a landscape greatly characterized by its variability (ALFA 2005; Pinto-Correia et al. 2011). Despite having been explored essentially as forest or silvopastoral (with higher densities) systems, it has been verified a reduction in density on many cork oak stands due to their decline as well as absence of natural regeneration (Camilo-Alves et al. 2013; Ribeiro et al. 2016; ICNF 2019a; Camilo-Alves et al. 2020).

While several studies focused on identifying the causes for this tree mortality, it is essential to understand how the loss of tree coverage affects the resilience of the system, which raises the question: considering climate change, particularly the reduction of precipitation, could the loss of trees benefit the system by reducing competition for scarcer water resources or, on the other hand, could it be further aggravated by removing its protective effect while in a positive feedback process? Considering these questions, the objective of this study was to analyze the relationship between cork oak mortality and crown cover by means of tree mortality events identification over time. In order to identify possible mortality trends, areas of decline were related to potential factors, such as soil type, topography and solar radiation.

2. Materials and methods

2.1. Study site

The study area corresponds to an area of 98,195.3 ha in the region of Tagus Lezíria, South of Portugal. The region is characterized by a Mediterranean climate with a typical hot and dry summer and annual averages for temperature and rainfall between 15–16 °C and 500–700 mm, respectively (Camilo-Alves 2014; Poeiras et al. 2021). The soils of this study area are mostly litholic, podzols or regosols (Ferreira et al. 2001). Regarding land cover, oak areas composed by forests and agro-silvo-pastoral systems occupy approximately 50.3% of the total area (Fig. 1). Concerning the natural potential vegetation of this area, it belongs to the dominion of the cork oak forest of the psamophile vegetation *Aro negleti-querco suberis sigmetum* (Costa et al. 2012).

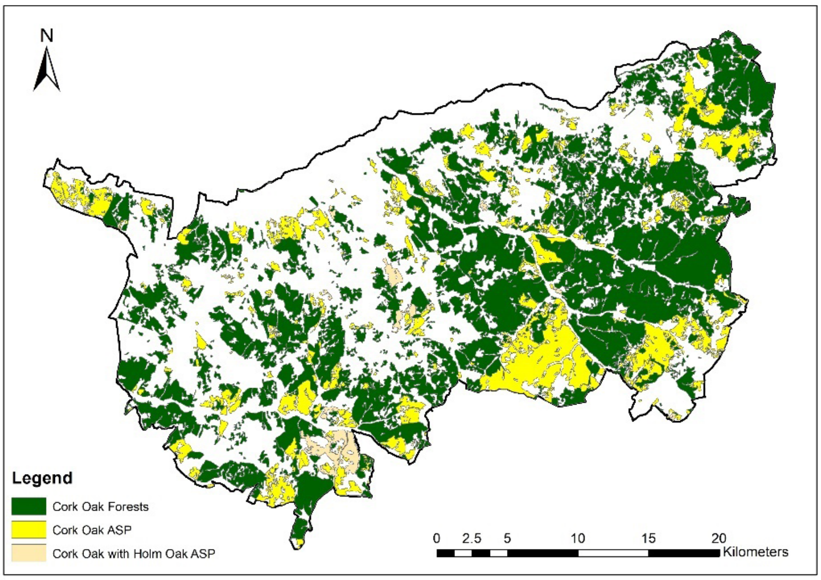

Fig. 1. Cork oak forests and agro-silvopastoral systems (ASP), in the study area, Tagus Lezíria, Portugal.

2.2. Image and map procedures

This work was performed in GIS (Geographical Information Systems) environment, using ArcGIS software, version 10.8.1 (ESRI). After extensive data acquisition, a pre-analysis was made and data treatment was performed in order to process the desired information through spatial and statistical analysis by producing several maps and a comprehensive and solid database, explained in further detail as follows:

Land cover and topography
Using Soil Cover maps (COS), obtained from the Portuguese National Geographic Information System (SNIG) database, a pre-analysis was done to verify whether changes in the soil use occurred within the study area, during the three studied time intervals (2004–2010–2015). The COS maps closest to the studied moments (years) were acquired, in this case, 2007, 2010 and 2015. Only the areas corresponding to "Cork oak forests" and "Cork oak agro-silvopastoral systems" (ASP) were analyzed.

The Digital Terrain Model (DTM) for Portugal, with a 25-meter resolution, obtained from the Portuguese Directorate General for the Territory (DGT), was used to characterize the hypsometry, slope and aspect of the study area:

- Hypsometry: altitude graphic representation of points over a reference plane;
- Slope: obtained from the DTM using the ArcGIS tool Slope. Afterwards, a classification was done, according to the cork and holm oak mortality inventories (Ribeiro & Surový 2008; Ribeiro et al. 2016);
- Aspect: obtained from the DTM, using the ArcGIS Aspect tool. They were divided in four quadrants (North, East, South, West), noting that the null aspect corresponds to a perfectly flat area.

Edaphoclimatic aptitude
Following the Regional Program for Forest Management (PROF) for Alentejo and Lisboa and Vale do Tejo regions (ICNF 2019b), the cork oak's aptitude was calculated by assessing the relationship between the species edaphic and climatic attributes.

Based on the Portuguese Soil Classification, each soil unit was classified according to its limitations regarding cork oak development (Ribeiro et al. 2016). Therefore, cork oak edaphic aptitude was determined according to the following table (Table 1), where the reference means that the specific diagnostic characteristics are neither favourable nor prejudicial to the cork oak development:

Climatic aptitude was calculated based on the relationship between three indexes (Pinto-Gomes & Paiva Ferreira 2005; Monteiro-Henriques et al. 2016; Rivas-Martínez et al. 2017), in this case, spanning 10 year intervals (1994–2004, 2000–2010, 2005–2015) and calculated from data collected from a nearby meteorological station (Table 2):

Table 1. Diagnostic of the soil characteristics regarding cork oak productivity.

Diagnostic characteristics	Cork oak
No limitations Limitations in depth, but expansible	Above reference
Shallow soils Textural discontinuity (clay in Horizon B) Reduced water storage	Reference
Reduced external drainage Reduced internal drainage Limestone Rock outcrop Salinity Social area Vertical limitations	Below reference

- Thermicity index (It) – it considers the winter's cold intensity, using the following equation:
  $It = (T + m + M) \cdot 10$ [1],
  where: T – mean annual temperature (°C); m – mean of the coldest month minimum temperatures (°C); M – mean of the coldest month maximum temperatures (°C);
- Ombrothermic index (Io): relates the mean annual precipitation (Pp) with the mean annual temperature (Tp):
  $Io = Pp / Tp$ [2];
- Continentality index (Ic): corresponds to the temperature's mean annual amplitude:
  $Ic = T_{max} - T_{min}$ [3],
  where T_{max} is the hottest month mean temperature and T_{min} is the coldest month mean temperature.

The final determination is based on the law of minimums between the edaphic and climatic aptitudes, resulting in the bioclimatic aptitude of this species for the study site.

Solar radiation
Considering that the increase in solar radiation directly reaching soil level could be a factor to the tree's decline (Bader et al. 2007; Pourhashemi & Sadeghi 2020), this variable was added to the analysis. The solar radiation map in matrix format was confined to the study area, and converted to vector format – polygons (without any reclassification). This map corresponds to the average of the Global Horizontal Irradiation daily total values from 1994 to 2018.

Dead trees and crown cover
The methods used for the identification of dead trees in the three studied moments followed the procedures and criteria applied for the "National Cork Oak Mortality Inventory based on the digital aerial photography of 2004/2006" (Ribeiro & Surový 2008; Camilo-Alves et al. 2020).

Provided by the Portuguese Geographic Institute, orthophotomaps (50 cm resolution) covering the region were processed according to Surový et al. (2004b) methodology, with ArcGIS software, resulting in a false colour

Table 2. Cork oak bioclimatic aptitude (ICNF 2019b) matrix obtained through intersection of three bioclimatic indexes. The continentality index's values correspond respectively to: 1 – Euhiperoceanic; 2 – Low hiperoceanic; 3 – Semihiperoceanic; 4 – Euoceanic; 5 – Semicontinental.

Thermicity index	Inferior Termomediterranean					Superior Termomediterranean					Inferior Mesomediterranean					Superior Mesomediterranean				
Continentality index	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
Ombrothermic index: Superior Humid	—	—	—	—	—	—	—	—	—	—	2	2	2	2	2	1	1	1	1	1
Inferior Humid	—	—	—	—	—	3	3	3	3	3	3	3	3	3	3	1	1	1	1	1
Superior Sub-humid	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	1	1	1	1	1
Inferior sub-humid	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	1	1	1	1	1
Superior Dry	3	3	3	2	2	3	3	3	2	2	3	3	3	2	2	—	—	—	—	—
Inferior Dry	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	—	—	—	—	—
Superior Semiarid	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	—	—	—	—	—
Inferior Semiarid	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	—	—	—	—	—

1 Below reference 2 Reference 3 Above reference

image by combining RGB (colour) (specific permutation) and NIR (Near Infrared) bands in which the contrast between vigorous and dead/decrepit trees is evident and cork oak identification is possible using its crown spectral signature (Surový et al. 2004a; Surový et al. 2004b). Dead tree identification was performed with visual detection and manual selection followed by the living cork oak trees' discrimination from the background (RGB colour space transformation) using the B-square index. Though its accuracy matches those of other indexes its overestimation error is lowest (Surový et al. 2004a). Such procedures produced diachronic maps figuring on one hand dead trees (polygon per dead tree) and on the other hand tree crown cover, later classified (considering an evenly distribution of the polygons among classes) as: less than 20%; between 20 and 29%; 30 and 34%; 35 and 40%; and greater than 40%. Crown cover is the percentage of area covered by the trees' canopy.

Tree mortality index

The tree mortality index (*MI*) for the three studied moments, relating the number of dead trees, the crown cover and the area is given by (Ribeiro & Surový 2008):

$$MI = \frac{\text{N}^{\circ}\ \text{dead trees per hectare}}{\text{Crown cover (\%)}} \qquad [4]$$

This index relates tree mortality to tree density, reaching higher values particularly when crown cover is much reduced (Camilo-Alves et al. 2020) and its values were divided in 6 classes, described as follows (Table 3):

Table 3. Reclassification of the tree mortality index into classes.

Interval (10^{-3})	Classes
[0–3]	1
[3–6]	2
[6–12]	3
[12–24]	4
[24–48]	5
>48	6

2.3. Statistical analysis

Databases were created using ArcGIS, where every characteristic was intersected (including the crown cover and tree mortality index), together with the identified dead trees on all three analyzed years, resulting in polygons with unique information regarding every studied variable. Given that forest areas must have more than 0.5 ha (FAO 2020; Decree-Law 169/2001), polygons with an area below this value were merged with its larger neighbouring polygon. Statistical analysis was performed using the SPSS v.24 software package and followed the methodology used in Camilo-Alves et al. (2020).

Diachronic study

A diachronic study regarding the evolution of the cork oak's mortality during the set interval (2004–2015) was performed, using a generalized linear mixed model, with robust estimation and repetitive measurements (the three analyzed years) where the target has a Gamma distribution with a log link. Only the polygons where tree mortality has occurred were analyzed. The objective was to analyze changes in MI intensity or occurrence from 2004 to 2015. This model estimates random and fixed effects. The tree mortality index is the dependent variable, the subject (tree) was the random effect and the fixed effects were the following:

- Exploration system: Forests or Agro-silvo-pastoral Systems denominated ASP;
- Global Horizontal Irradiation (GHI);
- Climatic aptitude of the cork oak (Cli_Apt);
- Edaphic aptitude of the cork oak (Eda_Apt);
- Polygon area;
- Crown cover.

Topographical variables (slopes and aspect) were excluded from the analysis due to their great homogeneity throughout the study area.

Analysis of the effects of climatic conditions for each crown cover class

In order to understand the effect of the crown cover on the relationship between edapho-climatic variables and tree mortality, each crown cover class was analyzed separately using generalized linear models. Tree mortality index was ranked using savage score tool.

2.4. Cadastre

A complementary analysis was made using the Geometric Cadastre in an attempt to empirically detect a spatial relationship between tree mortality and property. According to the General Management for the Territory (https://www.dgterritorio.gov.pt/cadastro/cadastro-geometrico-da-propriedade-rustica), the cadastre allows one to know the location of the lands, as well as their geometric configuration, area and confrontations. This analysis supported the comprehension of this phenomenon, namely the possible connection between tree mortality and stand management.

3. Results

The analysis indicated a slightly homogeneous topography with 99% of the area with gentle slopes (< 15%) and altitudes inferior to 195 meters. The area's aspect is also well distributed along the quadrants.

Regarding climatic characteristics, the study area has both Inferior Mesomediterranean and Superior Thermomediterranean thermicity indexes; Inferior Sub-humid and Superior Dry ombrothermic indexes; and Euoceanic and Semihiperoceanic continentality indexes (Pinto-Gomes & Paiva Ferreira 2005; Monteiro-Henriques et al. 2016). However, the calculated climatic indexes for the studied periods revealed a change in the region's climatic conditions (Fig. 2). Between 1994–2004, the region found itself with the Superior Dry ombrothermic index and with the Euoceanic continentality index. In other words, during this interval the (almost entire) area's suitability for cork oak shifted from above reference to reference. This situation was further aggravated from the 2000–2010 interval onwards when the climatic indexes changed the entire region's edaphoclimatic aptitude for cork oak into below reference, as the ombrothermic index corresponded to Inferior Dry (both in 2000–2010 and 2005–2015 intervals). Besides this, solar radiation is increasingly more intense in the West-East direction.

Regarding the identification of dead trees, there is a clear ascending tendency in number throughout the years with almost three times the difference between the first and second intervals (Table 4).

Table 4. Number of dead cork oak trees and crown cover area distribution during the studied period.

Year	Dead cork oaks (n)	Crown cover distribution (ha)			
		< 20%	20–29%	30–40%	> 40%
2004	2,751	1,980	11,879	36,423	321
2010	3,691	1,570	15,443	32,462	1,125
2015	6,224	2,308	11,002	36,292	997

Land cover presented no significant changes during the studied periods. Besides this, nearly 93% of the Agro-Silvopastoral systems (ASP) and cork oak forests had a crown cover between 20 and 40% with slight variations: between 2004 and 2010 the 30% crown cover areas suffered a 10% area loss; on the other hand, there was a slight increase of 5% and 3% in the 20% and 40% crown cover areas, respectively (Fig. 3, Table 4).

Regarding the tree mortality index, the classes with the lowest mortality values corresponded to less than 20% of the areas where cork oak mortality occurred, whereas almost two thirds corresponded to classes 4 and 5, and the class with the highest tree mortality index value corresponded to approximately 20%. These values presented very slight variations over time.

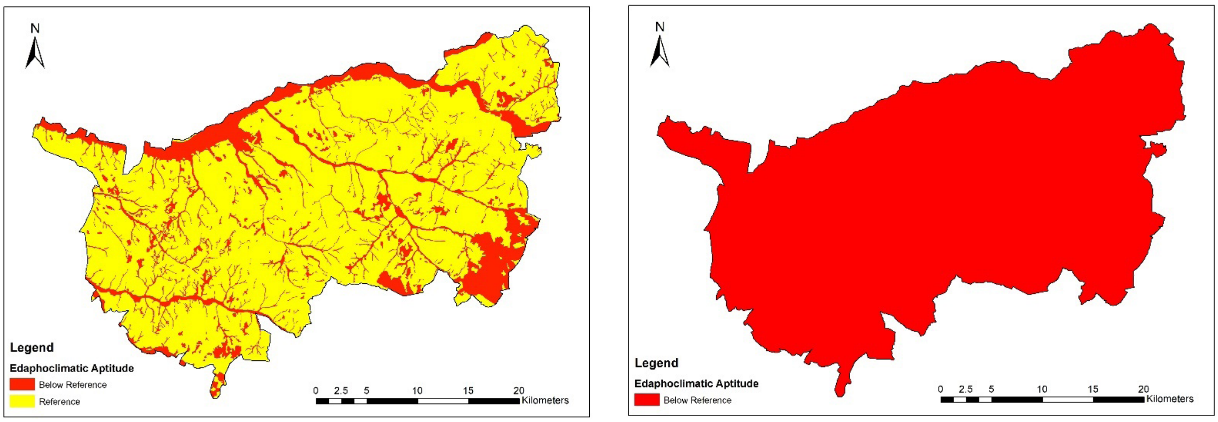

Fig. 2. Climatic aptitude for cork oak between: (a) 1994–2004; (b) 2000/05–2010/15 in the study area, Tagus Lezíria, Portugal.

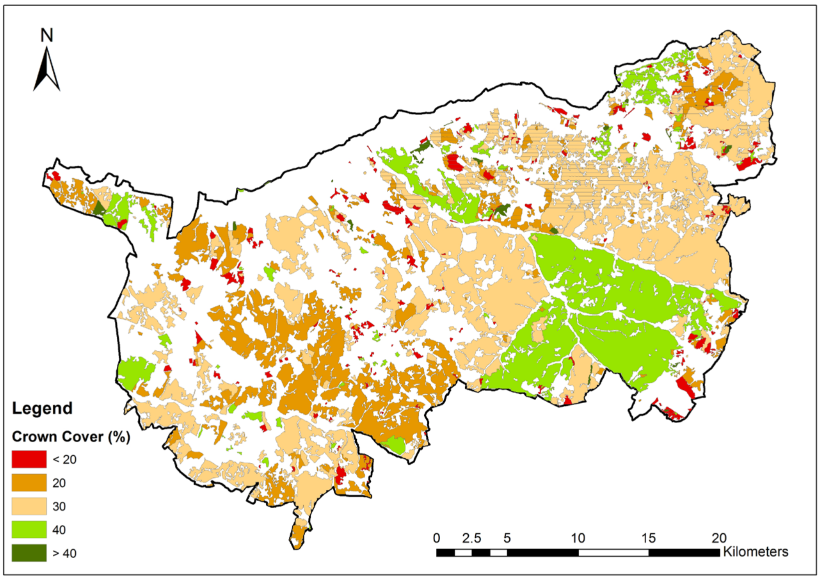

Fig. 3. Crown cover percentages in the forest and Agro-silvo-patoral stands, in the study area, Tagus Lezíria, Portugal, according to year 200.

3.1. Diachronic analysis of tree mortality

The only edaphoclimatic variables associated with cork oak mortality were the climatic aptitude, showing reduced mortality where climatic conditions were above reference (Fig. 4a, Table 5). Climatic indexes alone, land cover and edaphic aptitude, as well as the exploration system, were not significant. On the other hand, the relationship between solar radiation and tree mortality varied according to crown cover.

Table 5. Number of dead cork oak trees and crown cover area distribution during the studied period.

Source	F	df1	df2	Sig.
Corrected model	151	21	6,359	<0.001
Solar radiation	0[a]	0	—	—
Climatic aptitude	31.613	1	6,359	<0.001
Area	2,930	1	6,359	<0.001
Period	46	2	6,359	<0.001
Crown cover	3.466	4	6,359	0.008
Solar radiation * Crown cover	3.657	5	6,359	0.003

Note: a – This parameter is set to zero because it is redundant.

The crown cover exhibited a significant correlation with the tree mortality index which is to be expected, given that this variable was integrated into the aforementioned index to emphasize higher tree mortality in stands with lower crown cover. To accurately analyze the impact of the canopy on the relationship between edaphoclimatic variables and tree mortality, it is essential to conduct separate analysis based on the crown cover classes.

The area was highly significant as well due to the bias caused by the polygon dimensions up to 1 hectare, as revealed by the graphical analysis. This variable inclusion corrects this.

The diachronic approach showed an increase in the tree mortality index over time (Fig. 4b).

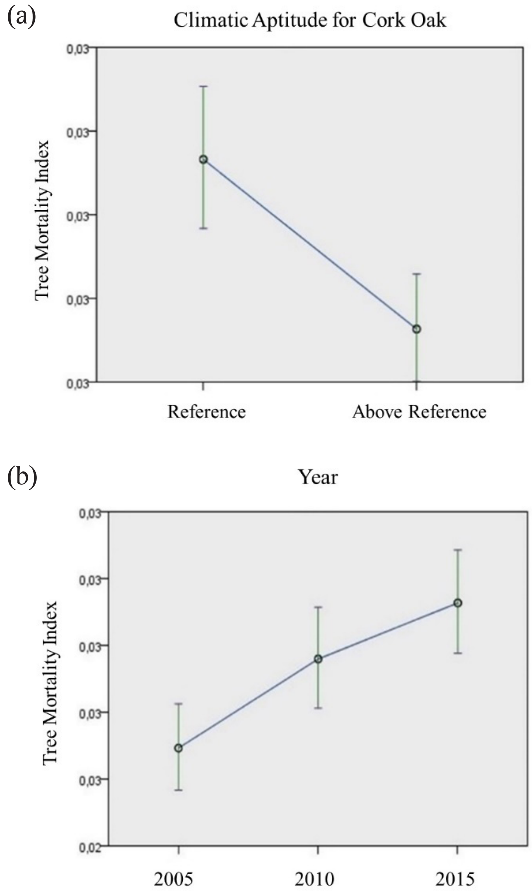

Fig. 4. Average and Standard error confidence interval of the cork oak mortality index for the mixed models, in relation to the: (a) climatic aptitude; (b) analyzed periods.

3.2. Crown cover influence on the effect of edaphoclimatic variables on tree mortality

In the areas with a crown cover inferior to 20%, no variable showed statistical significance. However, in stands with crown cover between 20 and 29%, the exploration system and climatic aptitude were significantly associated with tree mortality index (Table A1). As with the diachronic model, there was a higher mortality in the reference class than in the one above reference. On the other hand, the exploration system presented influence on tree mortality under these crown cover class as there was significantly less mortality in forests than in agrosilvopastoral systems (Fig. 5).

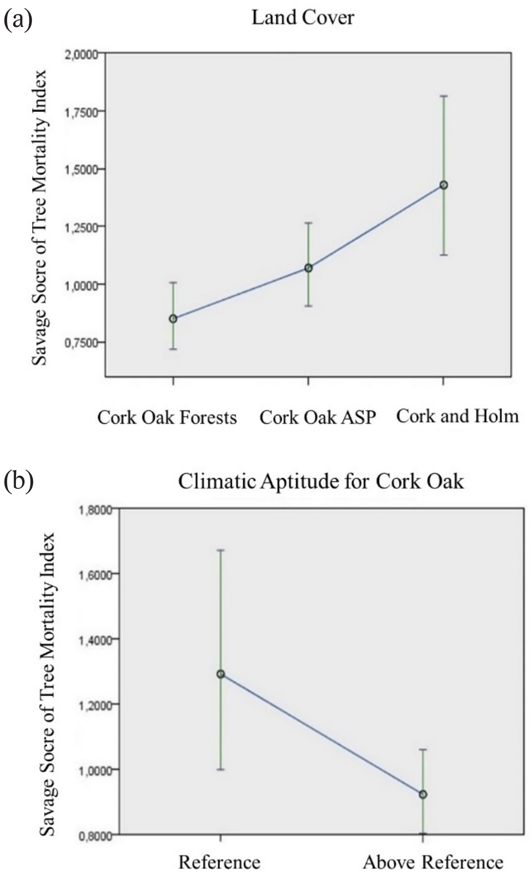

Fig. 5. Average and Standard error of the cork oak mortality index in stands with 20–29% crown cover, for the mixed models in relation to: (a) exploration system; (b) climatic aptitude.

For the next crown class (30–34%) only the climatic aptitude showed an association with cork oak mortality evaluation, with the same observed pattern than the previous class (Table A2). However, right above this class (35–40% crown cover), the solar radiation together with the climatic aptitude was also significantly associated with mortality (Table A3).

Finally, above 40% crown cover, no edaphic nor climatic variables were associated with tree mortality (Table A4).

3.3. Empirical analysis of tree mortality by property

Empirical observation is highlighted in figure 6, representing an area which maintained a high tree mortality density over time. In the first instant, there was a mortality cluster, in a valley's single slope; in 2010, it expanded to the West but, at the same time, maintaining a higher number of dead trees in the same property than that of its neighbours; finally, in 2015, this valley became a centre of expansion for the cork oak's mortality. It's noteworthy that the neighbouring property to the East barely presented dead trees in any of the three studied moments.

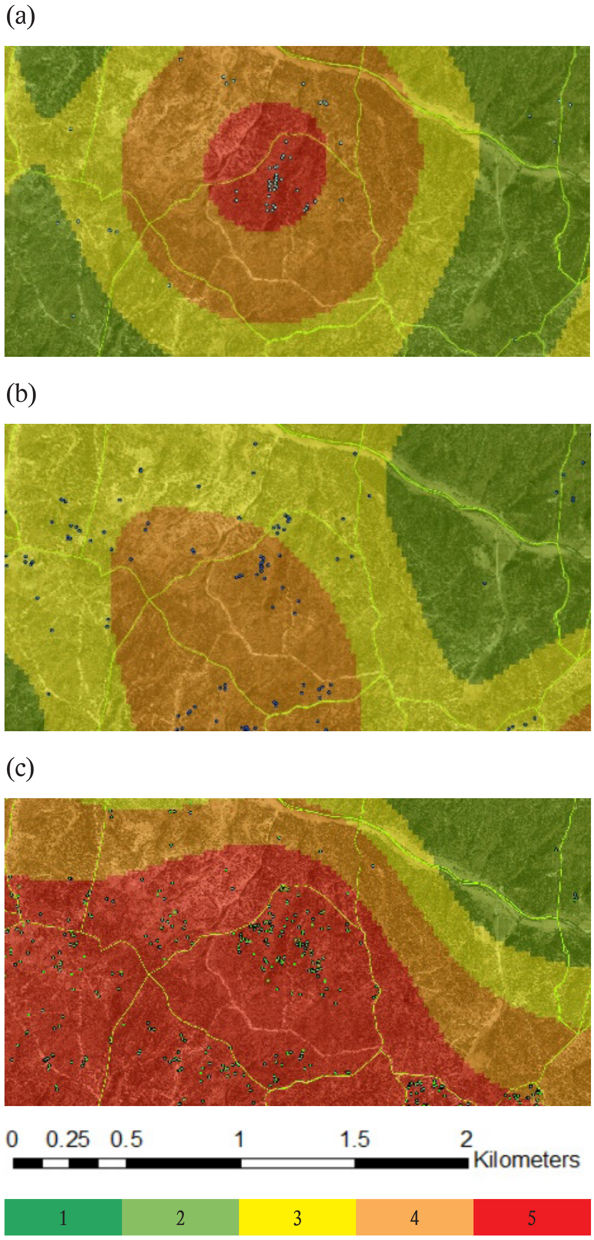

Fig. 6. Example of high tree mortality density connected to the CGPR over time. Dots correspond to dead cork oaks. Tree mortality density: 1 – Very low; 2 – Low; 3 – Moderate; 4 – High; 5 – Very high (a) 2004; (b) 2010; (c) 2015.

4. Discussion

The diachronic approach allows the study of tree mortality over time, associating it to the changes in the site's quality, in this case, according to the climatic conditions. The mortality rates increase over time, in particular in the areas with lower climatic aptitude, indicate the effect of the site's quality deterioration on the tree's vitality. The lowering of the ombrotype indicates a reduction in precipitation and, consequently, the reduction of the cork oak's climatic aptitude.

The study of the interaction between the solar radiation and crown cover allowed the understanding of how the climatic changes have differentiated effects depending on the stand's degree of tree coverage. Works by Príncipe et al. (2022) established the importance of local factors regarding crown cover, such as elevation and solar radiation, as well as by Pérez-Girón et al. (2002) which found that the canopy reduction may increase the cork oak stands' vulnerability to macroclimate conditions. In fact, they observed how a dense canopy can maintain microclimatic conditions making it less dependent of environmental conditions. Therefore, within the same ecosystem, response to climate change may vary depending on tree densities. In the present work, the stands with crown cover inferior to 40% were more vulnerable to these climatic changes, with higher number of tree mortality events whenever the climatic aptitude reduced. At the same time, the absence of such pattern in the denser stands (> 40%) suggests a protective effect. The crown cover reduces the solar radiation that hits the ground, thus reducing the soil's temperature and evaporation. This outcome holds significant importance in the context of forest adaptation to climate change. Tree thinning for water saving or to enhance trees' vitality may trigger an unexpected contrary response if 40% of crown cover is not maintained.

Moreover, the positive relationship found between the solar radiation and the 35–40% crown cover suggests that this interval limits the protective effect of the crown cover on the tree's vitality. Below this value, the variation of effect of solar radiation on the tree's vitality is similar for the amplitude found in the study area. The excess of solar exposure in Mediterranean environments, whether by direct or indirect effect, through temperature and evaporation increase, can have negative effects on the tree's vitality. This effect was observed in south exposing slopes, with greater solar radiation incidence than that from slopes facing other directions (Costa et al. 2009; Camilo-Alves et al. 2020).

Regarding land use, a significant relationship between cork oak forests/montados and tree mortality was observed. Great mortality densities coincided with the presence of large concentrations of agro-silvopastoral systems (ASP) in the southeast of the study area. The same pattern was found in other areas with similar concentrations of these exploration systems. As the main difference between both exploration systems (forests and ASP) is the agro-pastoral component, the results highlight its negative impacts on the forestry one, through inadequate cultural practices in these stands, e.g. harrowing, propagation of pathogenic agents on the soil, etc. Camilo-Alves et al. (2020) found that the soils with greater organic matter and/or nutrients content are less associated with decline, as they can promote the antagonist microbiane atmosphere to the pathogenic agents that attack the roots, emphasizing the negative impact of such cultural practices, since many of them, especially when intense, erode the organic matter and nutrients of the soil.

The effect of management can also be detected in the analysis of the cadastre delimitations (Fig. 6). The stands' incorrect management increases the vulnerability of the system in view of adverse climatic conditions, i.e. considering the decline's spiral (Camilo-Alves et al. 2013), the stands with conditions predisposing trees to decline, due to the worsening of the site's quality, become more vulnerable to temporary factors that incite vitality loss – e.g., poor management practices – thus occurring more mortality events. In order to avoid the loss of tree's vitality, correct and adequate practices regarding agro-pastoral management are of great importance, for example, avoiding soil mobilization (Ribeiro et al. 2010; Camilo-Alves et al. 2020) and excessive livestock (Godinho et al. 2016).

5. Conclusions

In conclusion, the diachronic analysis has shown how climate changes are increasing mortality in cork oak stands. Without a synchronic analysis, using the climatological normal values, the comprehension of mortality events in this region wouldn't be possible, nor would it be to adapt the management models to the new environmental conditions. The higher tree mortality on agro-silvo-pastoral systems indicated the effect of inadequate agro-pastoral management on tree vitality.

In the context of climatic changes adaptation, this study indicates that the forestry management models for the region should consider a 35–40% minimum tree coverage, in order to increase the resilience of the system, in order to achieve its equilibrium. Resilience is characterized by: "stand's structure and density dynamics over time, with a regeneration regime adequate to the management objectives and to the mortality rates, allowing the maintenance of a continuous cover" (Ferreira et al. 2007; Ribeiro 2015). Stand management is highly important for tree vitality, particularly in agro-silvo-pastoral systems (Ribeiro et al. 2004). Future research should focus on adaptive management practices concerning edaphoclimatic conditions in order to promote resilient forests to climate change.

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Appendix A

Table A1. Estimated parameters of the fixed independent effects of the dead cork oaks per hectare, for the mixed models, in the case of 20–29% crown cover.

Model Term	Coefficient	Std. Error	t	Sig.	95% Confidence Interval	
					Lower	Upper
Intercept	26.14	15.45	1.69	0.09	–4.17	56.44
COS = Cork oak forests	–0.52	0.11	–4.65	< 0.001	–0.739	–0.3
COS = Cork oak ASP	–0.29	0.12	–2.49	0.01	–0.52	–0.06
COS = Cork oak with holm oak ASP	0[a]	—	—	—		—
Climatic aptitude = 2	0.34	0.14	2.46	0.01	0.07	0.61
Climatic aptitude = 3	0[a]	—	—	—		—
Area	–0.49	0.02	–23.72	< 0.001	–0.53	–0.45

Note: a – This parameter is set to zero because it is redundant.

Table A2. Estimated parameters of the fixed independent effects of the dead cork oaks per hectare, for the mixed models, in the case of 30–34% crown cover.

Model Term	Coefficient	Std. Error	t	Sig.	95% Confidence Interval	
					Lower	Upper
Intercept	17.83	9.92	1.8	0.07	–1.62	37.3
Climatic aptitude = 2	0.36	0.06	5.99	< 0.001	0.24	0.47
Climatic aptitude = 3	0[a]	—	—	—	—	—
Area	–0.49	0.02	–31.42	< 0.001	–0.52	–0.46

Note: a – This parameter is set to zero because it is redundant.

Table A3. Estimated parameters of the fixed independent effects of the dead cork oaks per hectare, for the mixed models, in the case of 35–40% crown cover.

Model Term	Coefficient	Std. Error	t	Sig.	95% Confidence Interval	
					Lower	Upper
Intercept	–28.81	10.19	–2.93	0.003	–49.79	–9.83
Climatic aptitude = 2	0.19	0.06	3.07	0.002	0.07	0.32
Climatic aptitude = 3	0[a]	—	—	—	—	—
Area	–0.33	0.02	–21.00	< 0.001	–0.36	–0.30
GHI	6.36	2.18	2.92	0.004	2.08	10.64

Note: a – This parameter is set to zero because it is redundant.

Table A4. Estimated parameters of the fixed independent effects of the dead cork oaks per hectare, for the mixed models, in the case of over 40% crown cover.

Model Term	Coefficient	Std. Error	t	Sig.	95% Confidence Interval	
					Lower	Upper
Intercept	66.57	60.68	1.10	0.28	–53.57	186.70
Area	–0.37	0.06	–6.83	< 0.001	–0.48	–0.27